

# THE DUAL DIAPHRAGM PUMP

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## ABSTRACT

This paper reports a major advancement in gas pumping at micro- and meso-scale, made possible by the newly developed, electrostatically actuated, dual-diaphragm pump (DDP). The DDP uses a conformal pumping chamber and two electrostatically actuated, structured diaphragms, to achieve perfect rectification. The DDP demonstrates flow rates of about 30ml/min and a power consumption of about 8mW at an overall pump volume of about  $1.5 \times 1.5 \times 0.1 \text{ cm}^3$ . The DDP is fully symmetrical, having true bidirectional operation; has essentially zero dead space; and is fully scalable. For increased throughput the individual pumping channels can be built in 1D, 2D and 3D arrays. This feature allows the optimization of the individual pumping channel for best performance under electrostatic actuation, but allows scaling of the pumping rate to the desired level. Arrays of  $2 \times 3 \times 5$  pumps have been successfully demonstrated. A DDP array pumping 4 liters per minute will be about 4 times smaller in volume and will use about 4 times less power than the most advanced commercially available air pumps [3].

## INTRODUCTION

Recent advancements in chemical and biological sensing have resulted in large increases in sensitivity together with significant reductions in the size, weight and cost of the detectors. Portable systems capable of detecting traces of explosives at levels of fractions of parts per trillion have been demonstrated and applied to the land-mine detection problem [1]. Conventional explosive detectors are floor-mounted instruments, many cubic feet in size. Also, biological sensors capable of detecting one microorganism per cubic meter of air are now being developed. When vapor-phase analytes or air-borne particles have to be detected, a sampling system is generally used for increasing the probability of detection and reducing the detection time. The pumps have not been keeping up with the developments in sensing, and a reliable, small, low power, low cost, high pumping rate, conveniently shaped pump is more often than not on the wish list of system developers.

The ideal pump for portable systems should have a very large figure of merit (FOM), defined as pumping rate/power consumption/weight. Pressure heads of less than 1 psi would be enough to provide pumping through a filter or a restrictor. Also, for multi-sensor systems, arrays of highly packed pumps could give the system increased flexibility. In sampling systems using particle filters, bidirectional pumping is a highly useful feature as it provides filter-cleaning capability. In addition, the bidirectional pumping could be used as an added feature in smart sampling systems.

Our previously published mesopump has addressed many of the above requirements [2,3]. However, the mesopump used multi-chamber peristaltic pumping, having a lower pumping efficiency. In the newly developed DDP, by reducing the number

of chambers from 4 to 1, a three times reduction in size and 2 times reduction in power is achieved, while the pumping rate is about 50% higher for the same chamber size.

This paper will present in detail the structure, the operation principle, the fabrication and the measured parameters of the dual diaphragm pump. We will show that Honeywell's dual diaphragm pump represents an attractive choice for a large variety of portable systems.

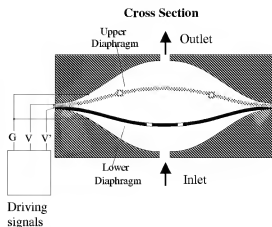


Figure 1. Schematic structure of the Dual Diaphragm Pump (DDP)

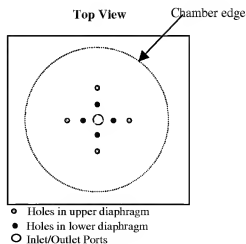


Figure 2. Relative placement of the diaphragm through-holes and of the inlet/outlet ports.

## OPERATION OF THE DUAL DIAPHRAGM PUMP

Figure 1 shows the schematic structure of the DDP. The pump consists of a chamber and two thin diaphragms. Each surface of the pump chamber and of the two diaphragms has a very thin metal electrode covered with a dielectric. The diaphragms have several through holes, which are non-coincident between them and non-coincident with the inlet and outlet ports (Figure 2). When either diaphragm is fully deflected and electrostatically clamped to the upper or lower wall of the pump chamber, it closes the corresponding inlet/outlet port. When the two diaphragms are clamped together, they move as a single sealed diaphragm, pushing the air in the desired direction. The exact operation sequence is described in Figure 3.

The electrodes from the upper and lower chamber walls are connected together to the electrical ground (G). The electrodes on the two sides of each diaphragm are connected together, resulting in the three electrical connections shown in Figure 1.

The operation has three phases. At the end of phase 3 (step 3a) both diaphragms are clamped to the lower wall of the chamber. This is achieved by applying a potential  $V$  to the lower diaphragm, while the upper diaphragm is connected to ground. In phase 1 the potential  $V$  is switched from the lower to the upper diaphragm, and the lower diaphragm is placed at ground.

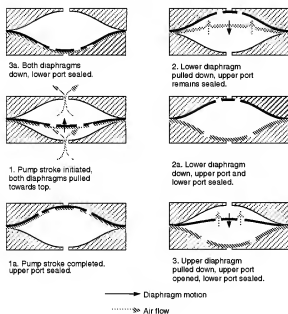


Figure 3. The three phase operation of the DDP

In this way, the diaphragms continue to be electrostatically clamped together, sealing each other's holes, but they start to move toward the upper chamber wall. During this phase, the air in the chamber is pushed out through the outlet, and at the same time, the air back-fills the chamber through the inlet port. At the end of phase 1 (step 1a), both diaphragms have touched the upper wall of the chamber, pushing out the entire volume of air in the chamber and sealing the outlet. In Phase 2 both diaphragms are connected at the driving potential  $V$ . This causes them to separate and the lower diaphragm moves toward the lower chamber wall. Because the diaphragm has through-holes with a

flow impedance smaller than that of the inlet port, no air is pushed back through the inlet. In step 2a the lower diaphragm is fully clamped to the lower chamber wall, sealing the inlet. In phase 3, the upper diaphragm is connected to ground, separating it from the upper wall and attracting it to the lower diaphragm. As in the previous step, because of the relative flow impedances of the diaphragm holes and of the outlet port, the diaphragm moves through the chamber without producing a net air intake at the outlet. At the end of phase 3 (step 3a) both diaphragms are clamped to the lower wall, and the 3-phase cycle can now re-start. The pump has essentially zero dead-space and provides perfect rectification.

## PUMP FABRICATION

The pump chamber is produced by injection molding. A large variety of plastics can be used to accommodate different application needs. Electrodes are deposited by evaporation and a thin dielectric material is deposited by ion beam sputtering. The diaphragms are made out of metallized Kapton. Thin dielectric layers are applied by casting. The pumps are mechanically assembled. The fabrication process is simple and reliable.

Large and deep chambers are being used in the current design to produce large pumping rates. Shallower chambers with a slightly modified profile and thicker diaphragms would result in higher-pressure heads [4].

## EXPERIMENTAL RESULTS

The following functional parameters of the Dual Diaphragm Pump will be reported: the measured flow rate per pump and its dependence on the actuation voltage and on the actuation frequency; the dependence of the flow rate on the direction of pumping and the pressure head.

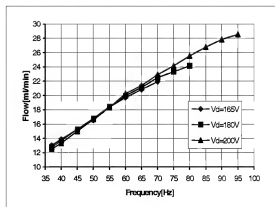
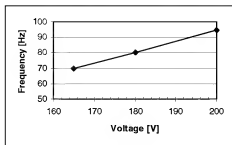


Figure 4. The dependence of flow rate on the operating frequency for different levels of driving voltage.

Figure 4 shows the dependence of the flow rate on the actuation frequency and on the actuation voltage. The pump has consistent and stable operation within its operating frequency range. This is different from other pumps where the direction of flow would change with variations in the driving frequency. Such devices could have stability problems across the temperature

range [5,6]. In the proposed DDP the flow can be reliably controlled through the driving frequency. Larger driving voltages allow operation at higher frequencies, resulting in higher maximum flow rates.

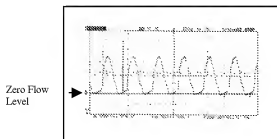


**Figure 5.** Measured dependence of the maximum driving frequency on the amplitude of the driving voltage

Figure 5 shows that inside the useful voltage range, the maximum driving frequency has a linear dependence on the amplitude of the driving voltage.

Figure 6 shows the time dependence of the flow, as measured with a Micro Switch AWM3100V airflow sensor, at an operation frequency of 66Hz. The measurement shows no back flow.

The rectification efficiency was evaluated by comparing the measured pumped air volume per stroke with the chamber volume as calculated from the geometrical dimensions. Precise information on the actual displacement of the diaphragm at different voltages and different actuation voltages was collected with a laser vibrometer. The measured volume per stroke at 66Hz and 200V actuation frequency is of about 5.5microliters. The pumped volume represents over 99% of the geometrical volume of the chamber when the exact displacement of the diaphragm is considered. This represents an improvement from the previously published mesopump, where a back flow of about 15% of the total flow was observed and the total volume per stroke was at about 75 to 80% of the chamber volume.



**Figure 6.** Pump flow vs. time as measured with Honeywell's flow sensor AWM3100V

The pumping rate has been measured in both directions for all the frequencies and driving voltages. Perfect symmetry in pumping is achieved, with the pumping rates being the same in both directions. The change in pumping direction can be achieved manually, through a switch or can be computer controlled. Any flow pattern (rate and direction) can be easily generated.

The pressure-head measured for the current design of the Dual Diaphragm Pump is about 20cm H<sub>2</sub>O. However, the pumps can be easily stacked on top to each other to produce pressure heads that are multiples of the pressure heads of the individual pumps. Also, as mentioned before, shallower chamber could be used in the applications where higher pressure heads are required.

The electrostatic actuators involving rolling contact are known to be difficult devices in terms of reliability. However, the structure, the operation mode and the materials used in the Dual Diaphragm Pump produced a reliable device. The pump has been operated with filtered air for days at a time without changes in performance. It has also been operated in non-filtered, room air for many hours without changes in performance. Detailed environmental and life testing is under way. Preliminary results show that variations in environmental humidity from 15% to 70% do not influence the operation of the pump.

An array of 2x3x2 pumps has been assembled. The size of the array is of 4.5x3.5x0.4 cm<sup>3</sup>. The measured pumping rate for an actuation voltage of 160V is of 230ml/min and increases with the driving voltage and actuation frequency. The overall size of the array can be further reduced if dedicated parts for the coupling of pumps are fabricated.

The power consumption per pump at maximum flow is about 8mW. The power consumption for the pump scales linearly with the driving frequency and with V<sup>2</sup>. The performance of the Dual Diaphragm Pump has been compared with commercially available pumps produced by KNF [7]. For pumps producing flow rates up to 300ml/min, the FOM, defined as Pumping Rate/Power Consumption/Size, for our pumps, is about 10 times better than that of the KNF pumps. For larger pumping rates (around 4liters per minute), the ratio approaches to 20.

## CONCLUSIONS

This paper introduces a new gas pump that can be considered as the most compact, the most versatile and the most efficient gas-pumping device at micro- and meso-scale. The pump is produced by plastic injection- molding, with post processing steps to create electrodes and dielectric layers. The device allows true bi-directional pumping, has virtually zero dead-space, and shows perfect rectification. The devices can be very easily connected in highly packed arrays for increased pumping rate or increased pressure head. Arrays of 2x3x2 have been demonstrated and 2x3x30 arrays are being assembled. The pumping rate of the individual pumps is not degraded when used in the array. The particular characteristics of this pump makes it an ideal candidate for portable and wearable applications. However, many other applications can take advantage of the low cost, low power and versatility of the device. The pump has shown good reliability. Complete qualification is underway.

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